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Non-invasive monitoring by ultrasound of liquid foodstuff to ice slurry transitions within steel ducts and pipes

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Abstract

Ultrasound was assessed as a non invasive method of detecting dynamic transitions occurring as a scouring high ice fraction ice slurry forces liquid food products through process lines. The attenuation of ultrasound waves passing through a test section was measured within a time window that captured waves with arrival times characteristic of a direct path through the tubing and its contents. A recording transducer measuring the attenuated signal provided an output in volts, corresponding to the extent of attenuation. Water as a comparable substitute for a liquid food product gave typical values of 2.32 ± 0.07 V for mean amplitude of these waves. The passage of ice slurry reduced this value to 0.75 ± 0.03 V which represented a highly significant ($p < 0.001$) reduction in transmission. Tomato soup under similar circumstances gave values of 1.93 ± 0.09 V reduced to 0.64 ± 0.02 V when ice slurry flowed between the transducers. Dynamic transitions involving yoghurt and yoghurt mixtures were also detectable except when the yoghurt and the ice slurry shared similar degrees of signal attenuation. Pipe geometry was typically found to introduce systematic changes to recorded values but these did not detract from the basic finding that significant differences were always found between flowing food products and ice slurry, except in the case of pure yoghurt in a large channel. Non invasive monitoring of dynamic product to ice slurry transitions in food grade steel pipes by ultrasound is readily achievable and could become a method of choice for product recovery systems.

Practical Applications

Ice slurries can be used to clean out foodstuffs from processing lines and offer the possibility of product recovery from within lines that would otherwise be lost by traditional cleaning methods such as water flushing. This process ideally needs non invasive monitoring in real time using on line sensors. External ultrasound transducers allow non invasive monitoring without changes to existing infrastructure. Food grade stainless steel presents a challenge to ultrasound due to the high impedance mismatch between it and liquid food products. Knowledge of the moment of transition is an advance on rudimentary timing methods and would help to minimise wastage with prevention of contamination in recovered product. Present work demonstrates that non invasive ultrasound can detect dynamic transitions to ice slurry within steel pipes and ducts, opening the way for automated control processes to minimise wastage and maximise product recovery.

Keywords: Ultrasound; Food product recovery; Food Pigging; Ice slurry, Stainless steel pipes

1. Introduction

In many industries, processing of fluid materials requires movement of product between different sites through ducts. It may be necessary periodically to clean such ducting because of accumulation of undesired deposits or because a change in the nature of the transferred product requires cleaning to prevent contamination. In recent years, the use of ice slurry ('ice-pigging') has been used to clean pipes and to extrude less diluted product from tubes in order to minimise wastage (Quarini, 2002). It can also be important to minimise the volume of waste product, if there are financial costs associated with large volumes of effluent that require processing to comply with environmental regulations.

Previous work has demonstrated the feasibility of using a pair of ultrasound transducers to monitor the transitions from food product to ice-pig and then to water as slurry forces food material through a borosilicate pipe (Lucas, Hales et al., 2015). The use of a chirp of ultrasound (Michaels et al., 2013) made it possible to obtain an almost instantaneous change in signal intensity as the ice-plug moved between the sensors. The laboratory pilot set up made use of clear borosilicate glass tubing to allow inspection of the materials as they

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passed between the sensors. The monitoring section was therefore necessarily not made of food grade stainless steel that is industry standard.

For these reasons, the ice-pigging process was examined using ultrasound in a system that more closely approximates a likely industrial setting. Channels of food grade stainless steel had ultrasound transducers attached using Perspex clamps. Two diameters of steel tubing were used to assess whether this altered the ability of ultrasound to distinguish between the materials moving between the sensors. Ultrasound sensors are flat whilst tubing is not and while attachment is always possible, the relative difference in curvature might alter the signal. For this reason, square ducts of comparable internal path length were used to investigate to what extent better physical contact of sensor to surface affects the measured signal. This present paper reports on work showing that the use of ultrasound is feasible in an arrangement that was purposefully closer to the likely industrial setting for the ice-pigging of food materials.

2. Material and Methods

2.1. Ice slurry manufacture and system topology

Ice slurry was manufactured by freezing a 5% NaCl brine solution using a *Ziegra* ice maker. This ice slurry was kept in a containment tank, with an attached hopper leading to a progressive cavity pump (Fig. 1). Piping led from the pump to a valve (1) which allowed either water from the mains or slurry from the tank to be flowing through the system. This valve connected to a plastic hose, leading to two valves (2 & 3) which regulated the length of ice slurry (1-3) during testing (3.25m). Product filled the remainder of the system (3-E) which could be varied in length depending on the hose present (4-S). Two lengths of hose were used, 2.75m and 14.75m, to investigate the potential effects of mixing. These hoses led to the test section (S-E) which comprised the 1m long steel channel through which ultrasound waves were passed.

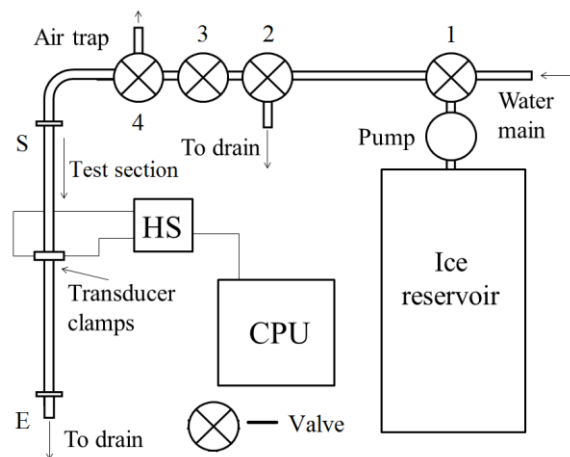


FIG. 1. DIAGRAM OF TESTING APPARATUS

2.2. Instrumentation

The test section routinely had a pair of ultrasound transducers fastened to it, which passed ultrasonic waves with centre frequency 0.7MHz through the section to interrogate the flow within. These transducers were fastened to the pipe using Perspex clamps manufactured in house, in differing conformations depending on whether the section was circular or square (Fig. 2).

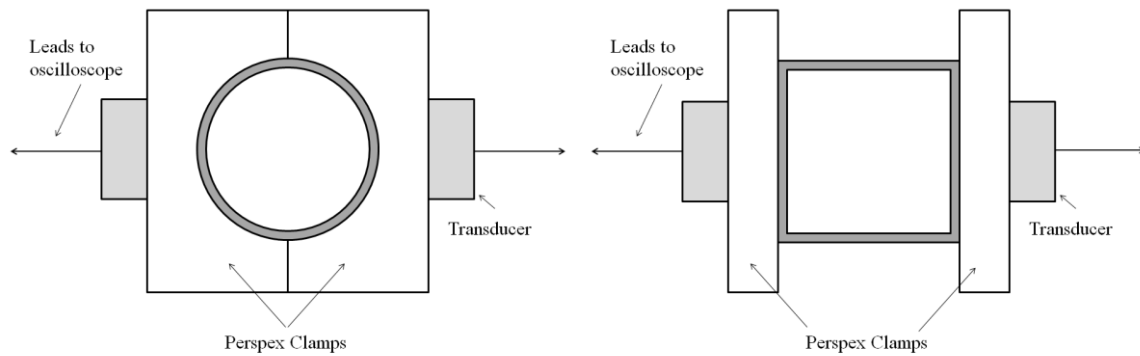


FIG. 2. CROSS SECTION OF STEEL CHANNELS SHOWING CLAMP ARRANGEMENT AND TRANSDUCERS FOR SQUARE DUCTING AND CIRCULAR TUBING.

The transducers fire waves through the test section according to parameters controlled by a connected digital oscilloscope. This digital oscilloscope, a *TiePie HS3 Handyscope*, was controlled by a CPU running a *Matlab* script. The oscilloscope was programmed to fire one transducer, which generated a series of ultrasound waves with controlled frequency, length and amplitude while recording at the opposite transducer for waves that had traversed the test section. This second transducer recorded over a set interval of time at a sampling frequency of 50MHz to exclude aliasing. This formed a received signal that was forwarded to the CPU and stored as a vector array. Firings were repeated several hundred times throughout each test. A 'test' comprised of the successful pigging of a food product from the system (Fig. 1; 3-E). The length of ice pig introduced was controlled by closing the valve (Fig. 1; 3) leading to the test section whilst pumping ice from the tank, until ice slurry flowed from the opened drain outlet (Fig. 1; 2). At this point, the valve (Fig. 1; 3) leading to the test section was reopened, the drain outlet (Fig. 1; 2) closed, and mains water was used to push the slurry from behind (Fig. 1; 1). A sufficient number of firings occurred to capture waves that had passed through the flowing sequence of pure product, contaminated product, ice slurry and then mains water. This meant that amplitude values of the received waves could be monitored in *Matlab*, during the test or during a subsequent processing period, to analyse what effect media change within the pipe had on the ultrasound waves. A series of these signals (Fig. 3) shows the changes in wave amplitude as ice slurry becomes present between the transducers.

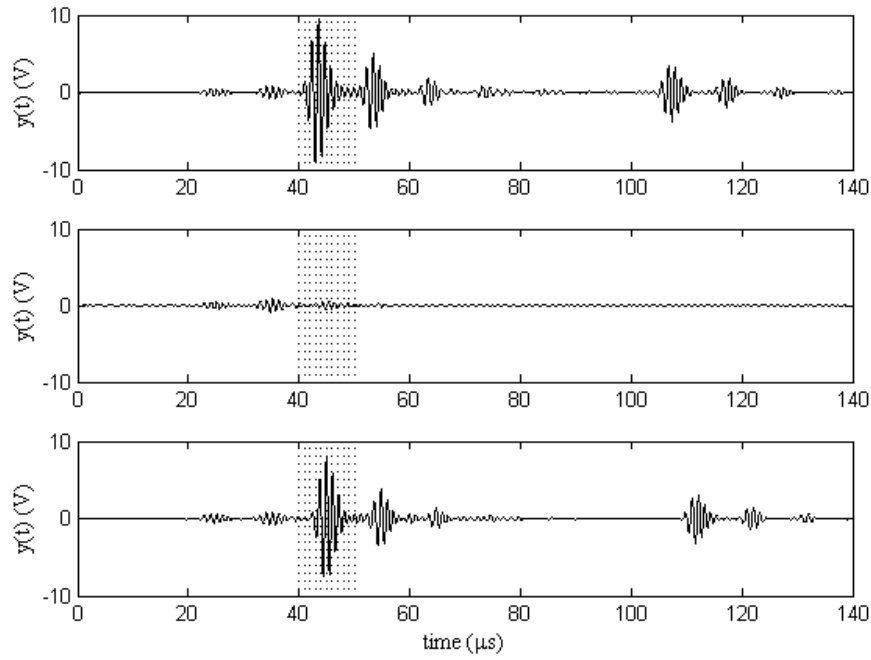


FIG. 3. SERIES OF SIGNALS RECORDED DURING A TEST. THE HIGHLIGHTED SECTION OF SIGNAL CORRESPONDS TO THE TARGETED DIRECT PATH WAVES. THESE WAVES HAD THEIR AVERAGE ABSOLUTE AMPLITUDE CALCULATED AND STORED FOR EACH FIRING. FROM TOP TO BOTTOM: TOMATO SOUP, ICE SLURRY, WATER

2.3. Signal processing

Distinct groups of waves are observed arriving at the transducer at times dictated by the combined acoustic properties of the Perspex clamps, steel channel and the interstitial media within. Internal reflections of these waves are also present, arriving at predictable intervals after the first arrival of waves at the transducer. When water is present within a two inch tube for example, the time of arrival (t_a) of waves which have traversed the test section by crossing between the transducers in a straight line ('direct path waves') was calculated to be at approximately 42.5 microseconds and is confirmed by inspection of the recorded signal (Fig. 3). The calculation (Eq.1) was based upon longitudinal wave velocity through Perspex (c_p), steel (c_s) and water (c_i) in combination with the thicknesses of each medium (d_p , d_s , d_i).

$$t_a = 2 \left(\frac{d_p}{c_p} + \frac{d_s}{c_s} \right) + \frac{d_i}{c_i} \quad (1)$$

To maximise the effectiveness of tracking transitions within the pipe, it was important to target only a section of the received signal. This is because large components of the signal were due to waves and their associated internal reflections that took indirect paths to reach the opposite transducer, with arrival times characteristic of passage through stainless steel or Perspex. Tracking the amplitude of waves that have gone directly through the central section of pipe can be achieved by selecting a signal window that spans their expected time of arrival as calculated using Equation 1. Not windowing leads to underestimates of wave amplitude and therefore is not as effective when monitoring the transition from food product to ice slurry. Since the arrival time of direct path waves is proportional to acoustic velocity, a time window was selected that was 11% lesser or greater than the arrival time through water of 45 microseconds, this being the arrival time of the largest wave in the sequence (Fig. 3). This was chosen because fluid food products have documented acoustic velocities that place them within this range (McClements & Gunasekaran, 1997, Shire et al. 2005a).

At each media interface, a fraction of the waves is reflected depending on the acoustic impedance, Z , of each medium on either side. The acoustic impedance describes a medium's resistance to the propagation of acoustic waves and is defined as the product of the medium's density and acoustic velocity (Kinsler et al., 2000). The longitudinal acoustic velocity in fluids is largely dependent on the density and bulk modulus of the medium

(Kinsler et al., 2000). The fraction of waves which pass through the interface is labelled the transmission coefficient, T , and these coefficients compound in series where propagation occurs through several interfaces. The variable T_{ab} represents the coefficient of transmission at an example interface from medium a to b , and is calculated from the reflectance coefficient, R_{ab} , which is in turn dependent on the acoustic impedance of both media as follows (Eq.2). This can be used to assess likely interfaces offering greatest impedance mis-matching.

$$T_{ab} = 1 - R_{ab} = 1 - \left(\frac{Z_b - Z_a}{Z_b + Z_a} \right)^2 \quad (2)$$

Knowledge of the transmission coefficients is important for calculating wave amplitude (Eq.3), where A_f and A_0 represent the final and initial wave amplitudes, as well as estimating the attenuation properties of the medium being interrogated. Variables α and d denote attenuation and distance within the individual media. Subscripts p , s and i refer to the Perspex, steel and internal medium within the pipe respectively.

$$A_f = A_0 T_{ps} T_{si} T_{is} T_{sp} e^{-[2(\alpha_p d_p + \alpha_s d_s) + \alpha_i d_i]} \quad (3)$$

As the acoustic wave propagates through ice slurry, several factors dictate the degree of amplitude loss. Absorption within the constituent phases (ice and brine) will convert some wave energy into heat through viscous losses. Additionally there are interfacial interactions between these solid and liquid phases. When the acoustic wave encounters the interface between them, there is a degree of transmittance and reflectance determined by the impedance mismatch of ice ($Z \sim 3.57$, Vaughan et al., 2003) and brine ($Z \sim 1.42$, Bradley, 1968). This can be calculated using equation (2), $T \sim 0.81$ $R \sim 0.19$. When reflection occurs, it can be either specular or diffuse. Specular reflection arises when the reflecting face is smooth and the size of the reflecting face is considerably larger than the wavelength of the incident acoustic wave (Sites et al., 2007). When the wave front interacts with rough faces and propagation obstacles that are of comparable size or are smaller than the ultrasound wavelength, diffuse reflection (scattering) will occur (Sites et al., 2007, Weill, 2014). This causes the acoustic wave to reflect off in multiple random directions and, more importantly, no longer in the original direction of propagation. The summation of the effects of scattering and absorption combine to form the attenuation capacity of a medium (Kinsler et al., 2000). When freshly made, the ice crystals within the slurry have diameters in the 100-200 micrometre range, although growth processes within the slurry can increase this by an order of magnitude if left for a significant amount of time (Pronk et al., 2002). The ultrasound waves propagating through the slurry have a wavelength larger than the ice particles ($\lambda \sim 2\text{mm}$ for $f=0.7\text{ Mhz}$ in brine $c \sim 1460\text{m/s}$) and so diffuse reflection, i.e. scattering, will arise at the brine-ice interfaces.

Small entrained air bubbles, inadvertently introduced into the slurry during production are also obstacles to propagation. These bubbles (approximate diameter 1-2 mm) will also cause scattering as they are the same order of magnitude as the acoustic wavelength. While it is impossible to distinguish between losses from attenuation due to absorption from that due to scattering in the experimental circumstances used here, it is likely that scattering will be a major factor reducing transmission, due to the relative size of the acoustic wavelength and propagation obstacles.

2.4. Individual and composite traces

For each firing, the amplitude of the waves in the windowed section was calculated. During a test, a line or 'trace' is formed, displaying how the amplitude of these waves rose and fell depending on what was present within the pipe. A typical trace fell sharply when ice slurry became present between the transducers, and rose again when water followed. Each test was repeated five times for each configuration of product or geometry. These individual traces were combined into a composite trace, which gave the average values of trace amplitude as well as the extent of amplitude reduction between product and slurry. The within-trace estimates of standard deviation were combined to give an overall standard deviation. This was multiplied by the appropriate statistical factor of 2.575 to give the 99% confidence limits. Movement outside this band would indicate the beginnings of deviation from expected values. Due to small variations in the length of slurry passing between the transducers, the secondary transition present in each trace from slurry to water required synchronisation before combination into a composite. This was done by removing part of the data prior to the transition point. This meant that there was no over estimation of the signal variance as ice slurry was replaced by water. The product region was typically the first 50 firings (roughly equal to two seconds). The ice region was the values existing before and after the obvious transitional regions appearing on the trace. The water region was typically the last 100-150 firings of the trace. For each series of tests conducted, a composite graph is presented in the results section.

3. Results

Results of pigging out water and food products are given in the following figures. Values for the mean and standard deviation are given for each individual product, ice slurry and water section in table 1 below. The length of hose present before the test section was 2.75m and where stated, this was lengthened to examine the effects of a length that allowed additional mixing of the ice slurry with food product.

3.1. Geometry tests

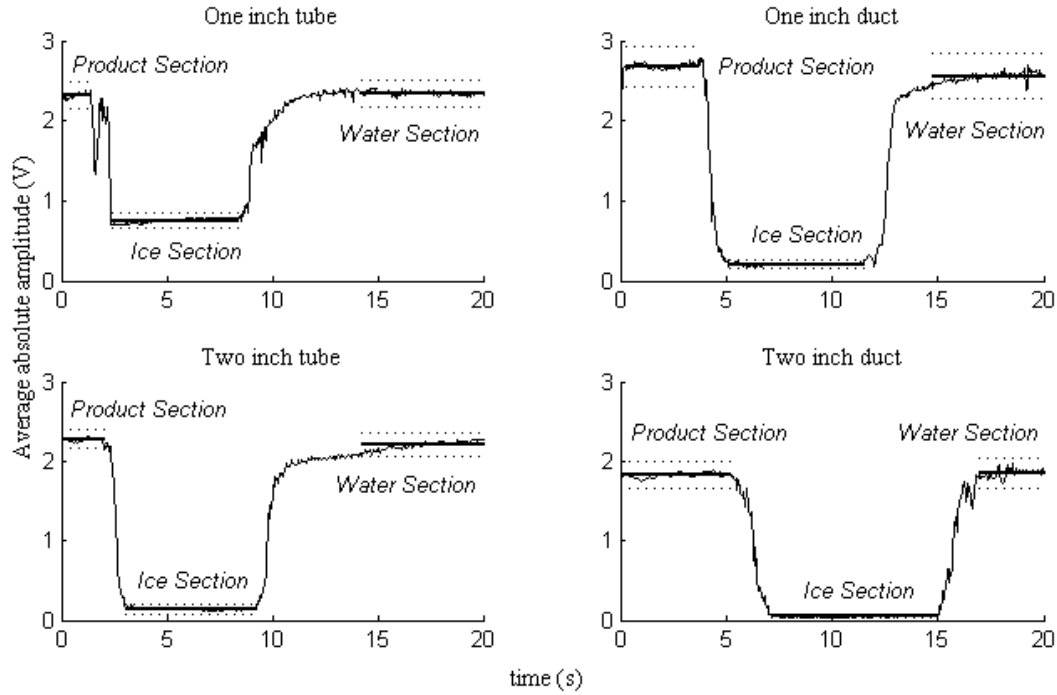


FIG. 4. THE EFFECT OF CIRCULAR AND RECTANGULAR GEOMETRY ON ULTRASOUND TRANSMISSION.

The first test was of water pigged from one inch steel tube. The average amplitude of waves through water of 2.32 ± 0.07 V (mean + standard deviation) showed a highly significant ($p < 0.001$) fall to 0.75 ± 0.03 V when ice slurry became present between the transducers, showing a sharp transition from water to slurry which was also seen on return to water (Table. 1). When the geometry was changed to one inch square duct, amplitude values through water rose (2.68 versus 2.32, Table. 1). Ice slurry amplitude of 0.21 ± 0.02 V was reduced significantly ($p < 0.001$) to about one third of that recorded through one inch tubing (0.75 ± 0.03 V). With two inch steel tubing, mean amplitude fell significantly ($p < 0.001$) from 2.28 ± 0.05 V to 0.14 ± 0.02 V when ice slurry was present. The transitional fall from product to ice was very rapid, occurring within a half of a second. With two inch square ducting, the transition from water product to ice slurry was also rapid, occurring within the time frame of approximately one second. The mean value of amplitude through ice slurry (0.04 ± 0.01 V) was the lowest recorded. Water before (1.82 ± 0.07 V) and after slurry passage (1.85 ± 0.07 V) was very similar. It was again evident that a clear, significant ($p < 0.001$) difference between flowing water and ice slurry could be measured despite high impedance mismatching at the steel wall.

3.2. Aged ice slurry, one inch tubing

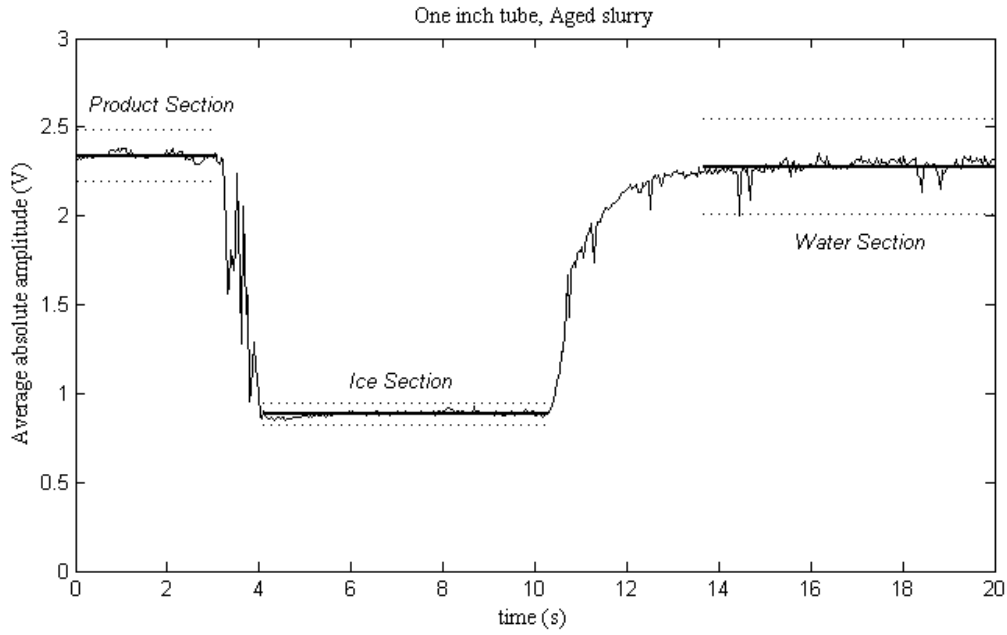


FIG. 5. THE EFFECT OF AGING OF THE ICE SLURRY IN ONE INCH TUBING ON TRANSMISSION OF ULTRASOUND.

Tests were conducted using ice slurry that was left to age, to determine the effect on amplitude. Pipe geometry was one inch tubing. The ice slurry value for aged slurry (0.89 ± 0.03 V) was significantly higher ($p < 0.001$) than fresh ice, although this difference was small and would be unlikely to impact on detecting the transition from product to slurry. This increase is likely due to the lower ice fraction of aged ice because some melting has occurred. A lower ice fraction reduces the bulk effective viscosity of the slurry, lowering the degree of absorption. Additionally there would be less scattering due to the reduction in ice particles. The amplitude increasingly moved towards values for water as might be anticipated.

3.3. Food product tests

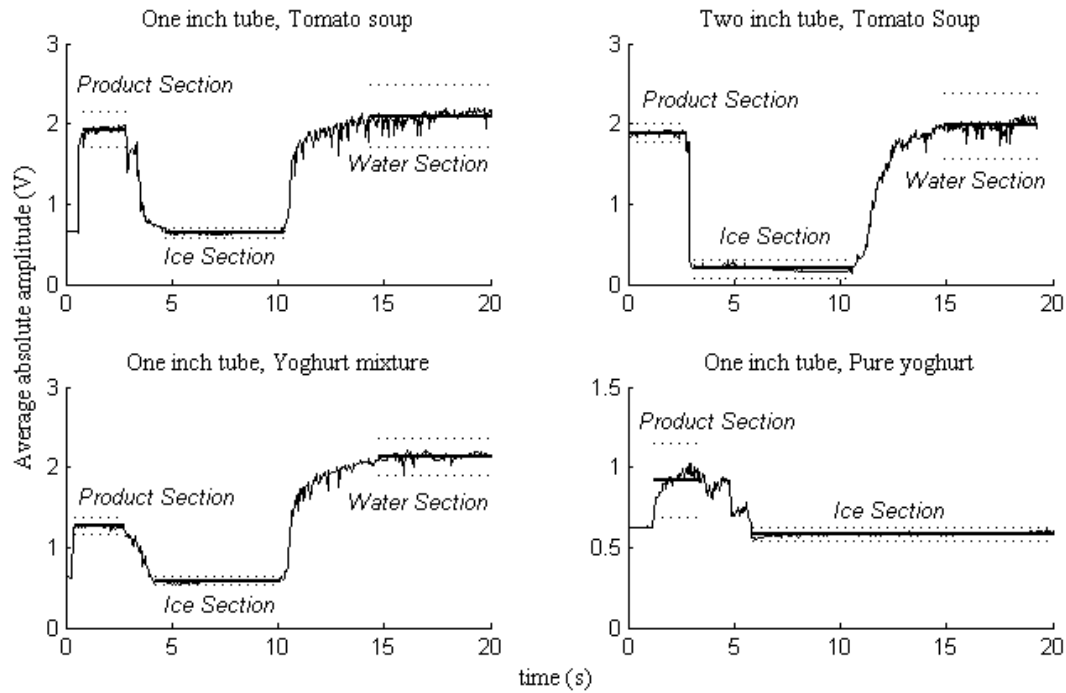


FIG. 6. THE EFFECT OF FOOD PRODUCTS IN TUBING ON ULTRASOUND TRANSMISSION.

When food products were tested, similar values were obtained. In the case of tomato soup, the mean amplitude was 1.93 ± 0.09 V and this rapidly fell significantly ($p < 0.001$) to 0.64 ± 0.02 V when ice slurry passed between the transducers (one inch tubing). When tomato soup was pigged through 2 inch tubing, amplitude significantly ($p < 0.001$) fell from 1.89 ± 0.05 V to 0.19 ± 0.04 V. It is interesting to note that the standard deviation in the amplitudes of soup in 2 inch tubing was less than that for 1 inch tubing. Transition times were again comparable. When a yoghurt mixture of 50% water by mass was tested in one inch tubing, the amplitude in the yoghurt mix of 1.27 ± 0.04 V was lower than through water (2.32 ± 0.07 V) but again there was a significant ($p < 0.001$) difference between product and slurry (0.58 ± 0.02). On pigging pure yoghurt, average amplitude (0.92 ± 0.09 V) was reduced further when compared with water but was still significantly ($p < 0.001$) higher than the ice slurry value of 0.59 ± 0.02 V. Transition time from product to ice slurry was slower as the ice slurry possibly was not as effective in scouring the yoghurt from the pipe.

3.4. Pure yoghurt, two inch tubing

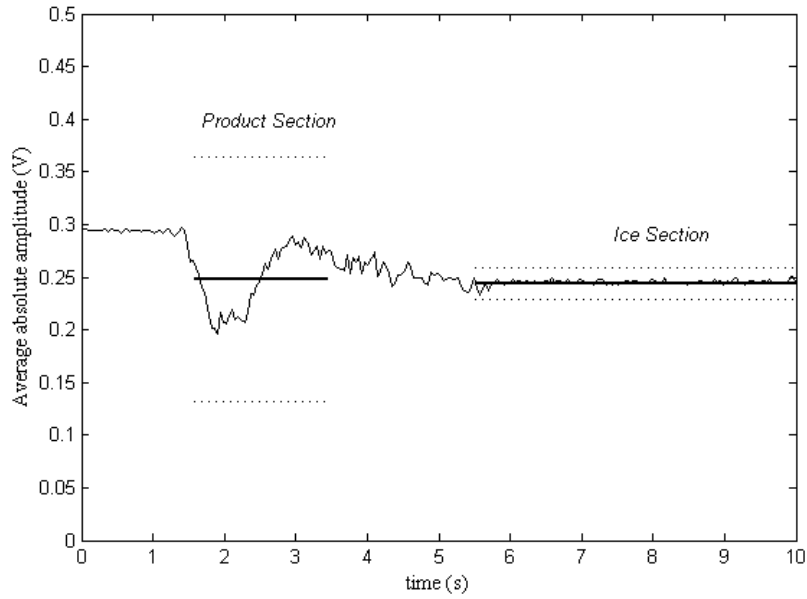


FIG. 7. THE EFFECT OF PURE YOGHURT ON ULTRASOUND TRANSMISSION THROUGH TWO INCH TUBING.

Pure yoghurt in 2 inch tubing proved to be problematic as the mean amplitudes through both product (0.25 ± 0.05 V) and ice slurry (0.24 ± 0.01 V) were very similar and discriminating between the two regions was not feasible from a statistical point of view.

3.5. Tomato Soup, one inch tubing, extended product section

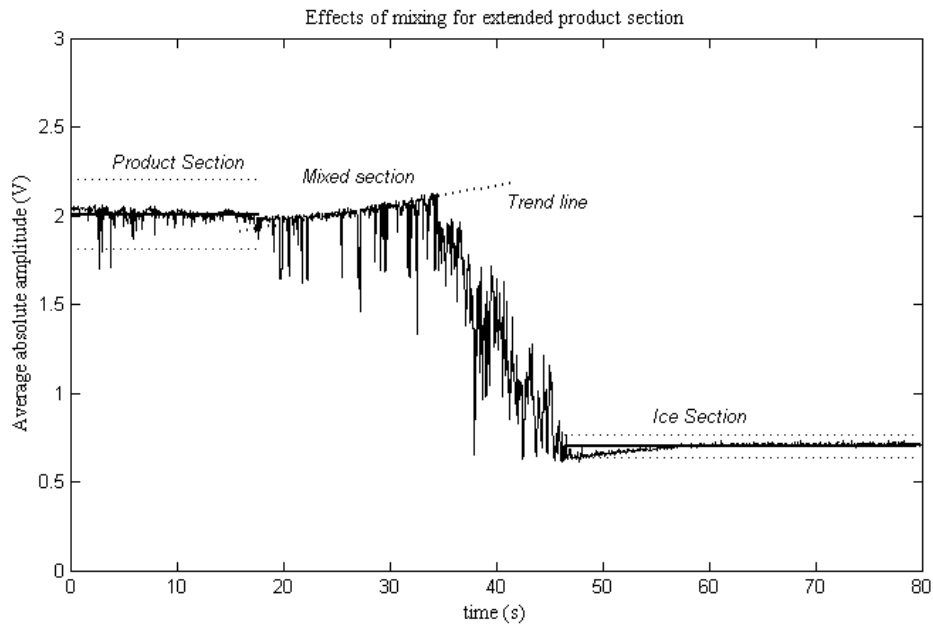


FIG. 8. THE EFFECT OF MIXING IN AN EXTENDED LENGTH OF PRODUCT.

When the length of section containing the product was extended to 14.75m, a higher degree of mixing was observed between the slurry and product. The transition period between product and slurry, where amplitude values begin to show a sustained fall in value, increased from 1.9s for the shorter length of tomato soup product in one inch tubing (Fig. 6. 2.8-4.7s) to 12s (Fig. 8. 34-46s). A mixed section is also present (20-34s), where

amplitude values trended upwards as progressively more dilute soup moved between the transducers.

3.6. Tabulated Values

The values displayed in the figures previously are presented here in tabular form for ease of reference.

TABLE.1. AVERAGE AMPLITUDE OF TRANSMITTED DIRECT PATH WAVES THROUGH MEDIA.

Product	Geometry	Diameter (mm)	Product Mean \pm SD	Ice Mean \pm SD	Water Mean \pm SD
Water	Tubing	25.4	2.32 ± 0.07	0.75 ± 0.03	2.34 ± 0.07
Water (aged ice)	Tubing	25.4	2.34 ± 0.06	0.89 ± 0.03	2.28 ± 0.11
Water	Tubing	50.8	2.28 ± 0.05	0.14 ± 0.02	2.21 ± 0.06
Water	Ducting	25.4	2.68 ± 0.10	0.21 ± 0.02	2.56 ± 0.11
Water	Ducting	50.8	1.82 ± 0.07	0.04 ± 0.01	1.85 ± 0.07
Tomato Soup	Tubing	25.4	1.93 ± 0.09	0.64 ± 0.02	2.09 ± 0.15
Tomato Soup	Tubing	50.8	1.89 ± 0.05	0.19 ± 0.04	1.97 ± 0.16
Yoghurt (50%)	Tubing	25.4	1.27 ± 0.04	0.58 ± 0.02	2.13 ± 0.10
Yoghurt (100%)	Tubing	25.4	0.92 ± 0.09	0.59 ± 0.02	--
Yoghurt (100%)	Tubing	50.8	0.25 ± 0.05	0.24 ± 0.01	--
Tomato Soup (extended)	Tubing	25.4	2.01 ± 0.08	0.70 ± 0.03	--

4. Discussion

The feasibility of using ultrasound to detect the transition from food product to ice slurry during transit, through stainless steel ducting or tubing, was investigated. Prior studies indicated that the transition from flowing water to ice slurry can be detected using ultrasound in steel piping (Shire et al, 2005b). Similarly there are measurements of pigging of food products traversing borosilicate piping (Lucas, Hales et al., 2015). What is reported here is the detection of the transition from flowing food products to ice slurry within steel channels. In almost every case, a significant difference existed between the mean recorded amplitude of waves passing through the products and the recorded mean amplitude of those through ice slurry. An additional point of note here is that the borosilicate study (Lucas, Hales et al., 2015) considered the whole of the signal and required further processing. In this study, windowing of the time signal was used to focus on waves that only traversed the central section in order to minimise the inclusion of ultrasound from indirect paths in the detection process.

For each food product or piping geometry, at least five traces were obtained. This allowed estimates of within-trace variance and also of between-trace variance, although in principle the latter was not required since the investigations were not seeking to assess between-trace variability as might be calculated in order to detect variations within a population of results (Sokal & Rohlf, 1995). Within-trace variance however was calculated, as was the standard deviation, of repeated measurements within any given trace, using standard methods, where the sum of the squared deviations from a product mean is calculated. The variance of the within trace error was averaged for all traces giving an estimate of the mean variance for all traces. This allowed confidence limits to be calculated for the composite traces and statistical tests to be undertaken. Using “Student’s” ‘t’-test, the statistical significance of the difference between mean values of amplitude through flowing food product and through flowing ice slurry were calculated. These differences in amplitude were highly significant as expected because the associated standard deviations of the within-trace errors were very small. The calculation of confidence limits has perhaps greater relevance to determining when a signal is moving out of normal bounds as would be required in any automated switching system.

When steel ducting was used as opposed to tubing for the smaller channels, there was an increase in the relative difference between mean amplitude values through product (water) and ice slurry. As the curvature of one inch piping is quite high when compared to the diameter of the transducers, a degree of deflection is predicted to occur to the longitudinal waves as they impact the pipe wall. This deflection may cause waves to travel through the Perspex clamps, and upon arriving at the opposite transducer, to be recorded along with any of their internal reflections within the analysed section of signal. This would not be the case with the square

ducting, as there is no Perspex available above or below the pipe for this to occur and additionally the geometry would hinder deflection. Thus a reduction in contribution from indirect path waves, as well as perhaps consequently an increased contribution in direct path waves within the analysed window would arise. It is noteworthy that amplitude readings through ice slurry in one inch tubing are significantly higher than through one inch square, despite the same internal path length. It is highly unlikely that more waves traversed the central path through tubing than the ducting. This suggests that some portion of the analysed waves when curvature is present, travel by indirect paths that may not traverse the central section of pipe work. A similar trend is seen for two inch geometry also, since amplitude is higher through ice slurry in tubing, although discernibility between a product and slurry would likely be reduced rather than enhanced by interrogating through ducting.

When tomato soup was tested as a proxy for water based food products, differences in amplitude were readily detected during the ice slurry passage through steel tubes, confirming that this method can be implemented within the industrial setting. When the length of product pigged was increased to 14.75m, the appearance of a section of brine-diluted soup was observed, caused by melt at the product-slurry interface during transit. Amplitude values trended linearly upwards as increasingly dilute soup was detected; as more ice particles became present between the transducers, the amplitude fell rapidly as was observed for shorter product lengths. This fall in amplitude was more protracted than before, taking an additional ten seconds for values to reach those characteristic of ice. While this longer period indicates the need for an increased length of ice pig to fully scour out the product (in this case tomato soup) when production lines are lengthier, significant amplitude differences were readily detected as before. The appearance of the upwards trend of amplitude values in the melt section perhaps points to a detection algorithm that keeps track of successively increasing mean amplitudes as an indication that diluted product is present between the transducers. A limit to the utility value of ultrasound was detected when pigging yoghurt. Yoghurt was chosen as a food stuff that was representative of foods with increased viscosity and lipid content (fat content 13.8% vs. 2.1% in tomato soup). The change from both fifty percent diluted yoghurt and undiluted yoghurt to ice slurry was readily detected in the smaller tubing. However, undiluted yoghurt in the wider tubing reduced recorded amplitude to a value that was very close to ice slurry. It is evident therefore, that certain food products may be able to reduce recorded amplitude to the level of ice slurry making the detection of change extremely problematic. This limitation has previously been described (Lucas, Hales et al., 2015) and means that shorter transmission path may be required when sufficient differences are not present through tubing of two inch diameter and above. In general however, ultrasound measurement of the dynamic transition from food product to ice slurry shows clear and statistically significant changes in amplitude during flow in stainless steel channels.

5. Conclusions

Externally sited ultrasound transducers are able to detect the transition from flowing food product to ice slurry in stainless steel tubing, making this non-invasive technique potentially useful in an industrial setting. Where food products have similar degrees of acoustic attenuation to ice slurry, interrogating through smaller channels is recommended and interrogating through ducting would aid the detection process as pipe curvature was shown to reduce the transmittance of direct path signal in the smaller diameter pipes. For larger channels however, changing to ducting had the opposite effect than was predicted: discernibility was reduced rather than enhanced. Channel shape relative to the transducers seems to alter the signal but nevertheless significant changes can be detected both in food grade stainless steel ducting and tubing. In process lines where only larger diameter piping exists, careful consideration of the foodstuffs being extruded would be necessary before implementation of the described ultrasound method of monitoring. As evidenced by the tomato soup data, interrogation through two inch tubing is preferred. This was not the case for pure yoghurt however, where the amplitude differences between product and slurry were only discernible through the smaller channel. Based on the curvature data, it is likely that a change to ducting in this instance would enhance the discernibility in the smaller channel. In industry where modification of existing plant is viable, the insertion of smaller ducting may allow otherwise problematic substances such as yoghurts with heavy lipid contents to be monitored.

In process lines of considerable length, greater mixing between tomato soup and slurry was observed and would need to be a consideration for any control algorithm. Mixing introduced a detectable rising trend in amplitude values which could be used to signal the onset of transition. In general, flowing food product in stainless steel gives very stable ultrasound values with a small variance; this feature would be advantageous for the design of a product recovery system.

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